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1979 SPRING REVIEW COURSE: PHASE TRANSFORMATIONS,
4-7 APRIL 1979, YORK, UK

JEFF PERKINS

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) The proceedings at the conference are reviewed, including papers on all classes of phase transformation, on new methods of research, and on examples of applications. Preceipitation, martensitic transformations, order-disorder reactions and other types of phase transformation are included. Other topics include morphological instability in micro-structures, phase transformations in ceramics, and the effect of industrial processing on transformations.		

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1979 SPRING REVIEW COURSE: PHASE TRANSFORMATIONS,
4-7 APRIL 1979, YORK, UK

International conferences devoted to the whole field of solid state phase transformations (PT) are rather infrequent. There have been only two such wide-ranging meetings in the UK in the last 25 years, in 1955 (London) and 1968 (Manchester). In the intervening years a number of conferences have been held on smaller segments of the PT scene, notably the particular type known as martensitic transformations, which, especially recently, has enjoyed a regular schedule of meetings (Toronto 1975, Kobe 1976, Kiev 1977, and Boston 1979). The last comprehensive PT meeting anywhere was in 1972 (Detroit). Therefore, a recent conference held in York (4-7 April 1979), which may be considered an extension of the prominent UK series, was long overdue and welcomed with great expectations by many metallurgists. The meeting was sponsored jointly by two UK metallurgical societies, the Institution of Metallurgists and the Metals Society, and attracted more than 150 delegates from a dozen or so countries. The manuscripts of most of the invited papers were collected in a conference proceedings Volume 1 that was distributed at the meeting, while Volume 2, containing the remaining contributions, will appear in a few months. Both volumes are readily available through the Institution of Metallurgists, Northway House, Whetstone, London N20 9LW, England. Therefore, this report will review the conference highlights in a general way, without too much detail of individual papers.

The fundamental definition of a phase transformation provided by J.W. Christian (Oxford University, UK), who gave the introductory lecture is as follows: A change in the macrostate of an assembly of interacting atoms or molecules as a result of some variation in the external constraints. Any such change must lead to an increase in the entropy of the universe and to a corresponding variation in the thermodynamic functions of the closed assembly. Perhaps a more obvious way to view the phenomena is to appreciate what a phase is, and then to realize that a phase transformation is simply a change in this state. A phase is usually defined by metallurgists as a structurally unique constituent of a microstructure, i.e., a region or regions with a given crystal structure, including exact specification of the lattice parameters. In metallurgical usage, therefore, the concept of a phase transformation simply implies that changes take place in the spatial configurations of the atoms (i.e., the crystal structure) and/or the chemical composition of regions of the microstructure.

Because of the wide variety of atomistic mechanisms by which such changes can occur, and the corresponding variations in reaction kinetics, resultant microstructures and properties (as a function of numerous variables, notably temperature and deformation history), PT research is one of the most exciting metallurgical fields of study, full of constant surprises and often requiring the deductive skills of a Sherlock Holmes. This conference reflected the usual intrigue of the field.

In addition to the fascination that attracts many researchers, one can argue that PT studies are the means by which physical metallurgists are trying to develop practical "heat treating" into a science, and in some cases this noble goal is being achieved in practice. In every case, however, the understanding of PT mechanisms constitutes part of the foundation of basic understanding that, if not essential, is at least useful for technological advances in materials. In other words, one may be able to develop a new heat treatment that produces a stronger steel without actually knowing the details of the mechanism by which the properties are changed, but if one does acquire knowledge of the mechanism, he will certainly be in a better position to control and optimize the properties.

The problem with organizing a conference on PT is that the subject is so far-ranging. It encompasses virtually all classes of metals and alloys (i.e., from A, aluminum to Z, zirconium) and a high proportion of the wide range of phenomena that relate to the technologically critical field of heat treatment. Therefore, such a conference cannot hope to be comprehensive, and the best program would be one that strives to quality, not quantity, of contributions. In other words, papers on virtually every active PT research project worldwide are probably not the goal the program committee wants to achieve. A better idea is to do as was done at this conference, and provide an excellent selection of overviews by prominent researchers in the field and a selection of the best current work. I suspect, however, that historically this 1979 meeting will not be regarded as much a landmark as were the 1955 and 1968 conferences. Several of the "big names" in the field were not in attendance, and the international balance was drastically skewed toward the UK (about 80% of the program), with suprisingly little contribution from three countries that are quite active and influential in the field, namely Japan, Germany, and the US, and (not suprisingly) no contributions were from the USSR or other Eastern bloc countries.

The conference was divided into about 10 sections, with an invited overview used to keynote each. These were prepared by J.W. Edington (Univ. of Delaware) on new techniques for PT research; H.I. Aaronson (Michigan Technological Univ.) on diffusional transformations; G.W. Lorimer (Univ. of Manchester) on precipitation in nonferrous alloys; R.W.K. Honeycombe (Univ. of Cambridge) on ferrous alloy transformations; W. Gust (Univ. of Stuttgart, West Germany) on discontinuous precipitation; M. McLean (National Physical Laboratory, Teddington, UK) on morphological instabilities; R.A. Buckley (Univ. of Sheffield) on order-disorder reactions; C.M. Wayman (Univ. of Illinois) on martensitic transformations; R.J. Brook (Univ. of Leeds) on transformations in polycrystalline ceramics; and T.I. Barry (National Physical Laboratory, Teddington, UK) on transformations in glassy ceramics. The papers by Honeycombe and Brook were read in their absence by colleagues. There were also two technology-oriented sections, on the effects of processing on transformation characteristics of commercial materials and case studies that demonstrate how PT research has contributed to the development of successive commercial materials. There also was a poster session and a memorable evening session dealing with microstructural nomenclature.

In phase transformations, the phenomena of most interest frequently occur on a very fine scale, so that advances in PT have generally followed the successive development of new higher-resolution techniques of investigation. The York meeting will perhaps be remembered as the conference of high resolution techniques, which are now being used widely to develop detailed transformation morphologies. In his review of advanced techniques for the study of PT, Jeffery Edington showed that although a wide range of techniques have been used, the most useful are those that combine quantitative measurements of composition and crystallography with direct microstructural observations. Electron-beam based methods have been the most successful and currently are being used widely. In his paper, Edington emphasized electron microscopy techniques, including such procedures as quantitative x-ray microanalysis, electron energy loss spectroscopy, convergent beam microdiffraction, and weak-beam technique. Also the capabilities of Auger electron spectroscopy and the atom-probe field-ion microscope were reviewed. Edington emphasized that the techniques tend to be complementary, i.e., no single technique will give all the information one needs; several techniques may often be used to develop a complete microstructural-crystallographic-compositional impression of the material under study. For example, x-ray microanalysis and electron energy-loss spectroscopy tend to be quite complementary in terms of the atomic number range where they are applicable.

This complete arsenal of techniques will cost an arm and leg, but with it one will be able to obtain diffraction patterns and crystallographic information from regions as small as 2 nm, detect very small lattice strains (10^{-4} nm), do chemical analysis on regions as small as 50 nm, detect microsegregation, image lattice planes directly, analyze a 1% surface monolayer, and many other amazing feats. Readers who wish further insight to the bases and to contemporary metallurgical applications of these techniques may be interested in two earlier notes (ESN 32-2:65, by Bernstein and ESN 32-10:351).

In a support paper in the advanced techniques session, Paul Butler (Imperial College of Science and Technology, London) described special methods developed to study phase transformations directly in the electron microscope, utilizing hot-stage equipment to transform specimens while being observed and recorded. (Bernstein has recently reported on other aspects of this *in situ* work at Imperial—see ESN 32-10:349).

Gordon Lorimer (Univ. of Manchester) reported on applications of quantitative analytical electron microanalysis, a subject that was the focus of a two-day meeting held at Manchester immediately before the York conference. The main application emphasized by Lorimer was partitioning of alloying elements in steels during the pearlite transformation. Groups at both Oxford and Cambridge have been developing the atom probe for PT studies. The atom probe is an instrument based on the field-ion microscope and is a microanalytical tool of ultimate sensitivity, in that one can identify single atoms. Furthermore, the depth profile of composition

from the sample surface inward can be acquired by successive field evaporation of the surface, and the lateral distribution of composition can also be displayed over the surface by developing the so-called field desorption image. The technique is therefore particularly suitable to the study of the very early stages of phase transformations. The work of the Cambridge group was exemplified by an excellent presentation by Sally Hill on order-disorder transformations in Ni-Al alloys, using primarily the depth-profiling mode; while the Oxford work, reported by George Smith and coworkers, has been applied to the chemical analysis of individual small precipitate particles as well as to ordering reactions and other transformations.

Hubert Aaronson (newly appointed R.F. Mehl Professor of Metallurgy at Carnegie-Mellon Univ., Pittsburgh), in his keynote paper on diffusional transformations, described his most recent results on the subject he has been studying for the last 20 or so years, work that has involved the pursuit of agreement between experimental data and models for growth kinetics, especially for grain boundary ferrite plates in Fe-C alloys. He also considered the subjects of interfacial structure and the role of shear in certain cases. Both of these are quite controversial contemporary topics and will certainly be given much further study, perhaps with the assistance of some of the aforementioned new techniques.

Lorimer's review of classical precipitation reactions in nonferrous systems emphasized spinodal decomposition and included descriptions of transformations in mineral systems (e.g., silicates, feldspars, and pyroxenes). Lorimer explained that the interest in these terrestrial minerals was inspired by the concentrated lunar rock studies that grew out of the US moon flights, by which methods to apply advanced techniques (e.g., TEM) were developed.

Ferrous transformations are the most technologically significant category of PT. Transformation from the high temperature austenitic phase to ferrite, pearlite, and other low-temperature phase mixtures occurs in millions of tons of steel each week throughout the world, and we now have, as a result of extensive research over the years, a reasonable understanding of the transformations. Honeycombe's keynote paper (presented by P.R. Howell of Cambridge) emphasized studies on the effect of alloying elements (elements other than Fe and C, the basic components of steels) on the important reactions, and there was also a number of related support papers from his ferrous group at Cambridge.

Gust presented an amazingly thorough (460 references) review of discontinuous precipitation in binary reactions. Perhaps unfortunately, he clouded the exposition by including certain reactions that do not correspond to all the classical ideas about this mode of transformation. The classical type of discontinuous precipitation begins at high angle grain boundaries and at free surfaces and consists of movement of an

incoherent phase boundary that leaves behind a two-phase mixture comprising the original phase and one new phase. Gust also identified another type of discontinuous reaction, which he called the "dislocation type," in which high-angle grain boundaries, sub-boundaries, and dislocations serve as preferential nucleation sites. This inclusion received some serious criticism in discussion.

Buckley pointed out that order-disorder transformations are perhaps more difficult to study than other modes of PT, and his paper emphasized work at Sheffield on Fe-Co alloys, using x-ray diffraction, TEM, and other techniques, with detailed studies of antiphase boundary morphologies and microstructural modes of the process of ordering as a function of temperature, annealing, cold work, quenching, etc. Various recent models for ordering were also discussed.

The word "morphology" by dictionary definition includes both the structure and shape of things, but as used by metallurgists refers only to the shape of phases (for a total microstructure the morphology refers to the size, shape, and spatial distribution of all the phases, i.e., to how it "looks") without reference to crystal structure within these shapes. Morphological instability in microstructures refers to transformation phenomena (such as dissolution of phases, coarsening, change of phase shape, etc.), by which metastable microstructures evolve toward a lower energy equilibrium state; these changes are often quite undesirable (except in certain instances such as hot working, where it is desirable for the structure to change quickly to a workable state) because of the properties changes involved. The importance of this subject was emphasized in a recent symposium sponsored by the Institution (see *ESN* 33-3:106) and of course, in the review given by McLean at this conference. McLean's analysis was essentially phenomenological, with no consideration of interface structures and such. Using mass transport analysis, he considered cases such as particle coarsening and breakdown of lamellar or rodlike morphologies in aligned eutectic microstructures. He also made a distinction between intrinsic instabilities that are driven by free energy changes resulting from a reduction in defect density in the material and intrinsic instabilities driven by external forces such as temperature and stress gradients.

Martensitic transformations have their primary importance in connection with the development of high strength in steels, although there are also martensites formed in numerous nonferrous alloys. Wayman's review was biased toward work in nonferrous systems and included discussion of pre-transformation phenomena, nucleation, crystallography, and morphology (backed up with an excellent film of thermoelastic martensite growth), the shape-memory effect, and recent studies on transformations which are crystallographically similar to, but not (by pure definition) actually martensitic. In this last category, for the example of the transformation of vanadium-hydrogen solid solution to vanadium hydride, Wayman presented perhaps the first proof of a case where both shear and diffusion are involved

in the transformation mechanism. The theory of nucleation of martensitic transformation is in a poor state, as alluded to by Christian in his opening talk, and the conference did little to shed light on the question, with the exception of an interesting paper by J.W. Brooks and coworkers (Univ. of Birmingham, UK) which involved *in situ* TEM studies.

Some other interesting contributed papers included an impressive study of a sequence of phase transformations in Zr-Ti alloys by S. Banerjee (Bhabha Atomic Research Center, India), work on ferrite-to-austenite transformation (reverse to the direction usually studied) in a stainless steel by P.D. Southwick (Univ. of Cambridge), early growth kinetics studies of plate precipitates in aluminum alloys by R.D. Doherty (Univ. of Sussex), interface phase transformations in $\alpha:\beta$ titanium alloys by C. Hammond (Univ. of Leeds), microanalytical studies of austenite decomposition by R.A. Ricks and coworkers (Univ. of Cambridge), precipitation reactions in ferritic steels by A. Hebdry (Univ. of Newcastle upon Tyne), and martensitic morphology in rapidly solidified ferrous materials by B. Cantor (Univ. of Sussex). The session on industrial processing included papers related to aluminum alloys, steels, and superalloys, and the case history sessions included reports on the development of ultra-high-strength steels, TRIP (transformation-induced-plasticity) steels, and shape-memory alloy devices.

In recent years it has become fashionable for metallurgists to broaden their horizons and become "materials scientists," a title that if taken literally encompasses an impossibly wide range, but which in practice usually means that attention is paid to ceramics and polymers as well as to metals, and that attempts are made to consider this range of materials in a common framework, acknowledging both similarities and differences in their fundamental bases. Thus at this conference a section on phase transformations in ceramics was included for the first time, and although it was not a particularly strong part of the program, there are enough similarities between the phenomena in metals and ceramics that in principle it is sensible to make this inclusion. As for metals, investigatory techniques have become critical, and have led to confirmation of various phenomena. Advances in specimen preparation techniques for TEM and the use of high-accelerating voltage microscopes have now made it possible to examine ceramic microstructures on the same fine scale as metals which is, as mentioned before, the scale at which the important phenomena are occurring. In fact, the ceramic session probably seemed a bit weaker than the metals sessions only because many of the papers reflected the more macroscopic and indirect characterization techniques on which ceramists have had to depend in the past.

On the whole, the York conference was certainly a memorable one. Among other delights it illustrated that in the ten years since the last PT conference dramatic advances in techniques have been made, and the theme emphasized throughout was the importance of structural and

compositional observations. Numerous papers were keyed to the use of sophisticated high-resolution techniques for direct study of phase transformation mechanisms, sometimes directly at the atomic level. Indirect and macroscopic techniques such as electrical resistivity, calorimetry, and dilatometry, seem to be used only in a secondary vein these days, and their utility was directly pooch-pooched several times in discussion. The latest high-resolution studies are leading to the replacement of some of the classical phenomenological models for phase transformations with detailed mechanistic description. Another interesting aspect of this conference, which generally tends to be true of PT meetings, is that micro-structure-properties studies were not very visible. This may seem surprising in view of the key goals of detailed PT characterization, but in fact, the York meeting probably did much better than previous meetings in addressing the vital research/technology crossover in the PT field, with help in this vein given by a healthy level of participation from an active industrial contingent in the UK. The conference confirmed that the study of phase transformations is both interesting in its own right and important as a basis for understanding how heat treatment can produce useful changes in the properties of materials. It is certain that this field will continue to be a highlight of materials science research in the future.